Experiments on Stream-line Motion in Curved Pipes.

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Author's previous Experiments.—In the paper read by the author on the "Flow of Water in Curved Pipes," before the Royal Society on June 2, 1910, it was shown that even a small curvature in the length of a cylindrical pipe affected the quantity of flow of water through the pipe. The effect at velocities below the critical velocity for a straight pipe was most remarkable, inasmuch as the experiments showed that in coiled pipes there was apparently no critical velocity region, whilst in less pronounced curves, where the critical velocity is not entirely absent, a very slight sinuosity of the pipe lessened the flow. This was shown by the increase in the value of the index n in the formula, $s = \mathrm{K}v^n/m$ from $n = 1$, for perfectly straight pipes, to $n = 1{\cdot}1$ to $1{\cdot}2$ for pipes slightly curved or sinuous. Here s or h/l is the hydraulic gradient, v is the velocity of flow, m is the hydraulic mean radius, and K is a constant.

In an attempt to discover the cause of this departure from the law of flow in straight pipes, the author had tried Prof. Osborne Reynolds' colour-band test in a coiled glass tube, but the arrangements were of a primitive character and the results obtained were not decisive. At the suggestion of Sir Joseph Larmor the colour tests have been repeated with specially made glass tubes, in which the stream motion could be traced by the introduction of coloured water through capillary nozzles.

Arrangements for Coloured Filaments.—The following arrangement was adopted:—A brass tube A (fig. 1) of about 2 cm. internal diameter was fitted internally with a piece of brass B of boat-shaped section, into which six separate supplies of dyed water could be introduced through the nipples shown in fig. 1. The dye was supplied from the open tubes T, the height of each of which could be adjusted so as to allow the dye to flow in a gentle stream from the nozzles N, N, which were 1·25 mm. external and 0·3 mm. internal diameter.

The supply of water came from a tank through a cock at C; to this was connected the pipe which contained the nozzles. The water from the tank in its passage past the nozzles carried the dyes with it. The direction of flow is shown by the arrows, the velocity of flow was regulated by a pinch-cock PC placed on a flexible tube at the outlet end of the tube under

observation. Glass tubes of various shapes could be connected at the joints J, J, and the stream-line motion made visible by the dyes could be observed and photographed or sketched.

In order to trace the paths of the streams of dye from each nozzle separately, six different colours were used, the nozzles and supplies of colour being so arranged that the stream from each could be observed separately; by an adjustment of the tube which contained the nozzles, every part of the tube could be investigated.

In fig. 1, six streams of dye are shown passing through the conical glass

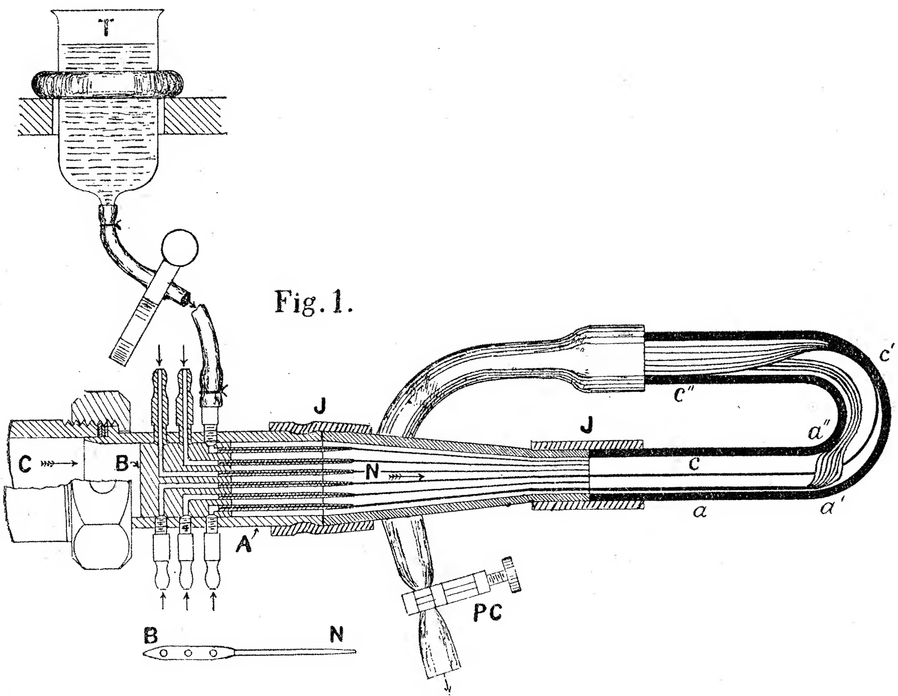

Fig. 1.

connecting tube JJ; the paths of two only of the filaments are traced in the U-tube. In fig. 2 the complete paths of six such colour bands are traced.

The first tubes experimented on were U-shaped, as shown in figs. 1 and 2; the experiments in these tubes are described in detail, since they illustrate the methods adopted for other curved tubes.

For the purpose of observing and photographing the stream-lines, the U-tube, with its central plane horizontal, was placed in a tank; mirrors with their planes at an angle of 45° with the plane of the U-tube were arranged in positions for obtaining the side and end elevations. In order to lessen the effect of refraction, the tube was completely covered with water; photo

graphs were taken of the tube and the reflections, and sketches were made from which fig. 2 has been drawn.

The photographs and drawing show the character of the stream-lines, but it is impossible to reproduce the extremely beautiful effects due to the interlacing of the colour bands. Although each band kept distinct from the others it was necessary when tracing out the stream-lines to shut off all the colour bands except the one under observation.

Results obtained in U*-tubes.*—A stream filament *a* (figs. 1 and 2) if it is in the central plane of the tube and close to the outer wall of the bend, breaks up into two parts immediately it reaches the curve of the bend, each of which leaving the central plane in opposite directions and following the wall of the tube crosses to the inner wall, and coming towards the central plane the divided filament forms the loop shown in the end elevation of the bend (fig. 2); the filament is now spread out into a narrow band and passes through the outlet limb, the path taken being shown by the lines *a*, *a*.

Stream filaments which are near the outer wall of the tube and just above (or below) the central plane will cross the bend as shown by the line *b* (fig. 2), and follow the surface of the tube, keeping above (or below) the central plane.

The behaviour of other filaments which are not in the central plane of the tube may be seen from the paths of *c* and *d*. Both these lines strike the outer wall of the bend and cross over near the surface of the tube, *c* to the inner wall of the bend and *d* to the inner wall of the outlet limb. The filaments *e* and *f* pass around the bend and do not strike the walls.

Several U-shaped tubes, right angled bends, and other tubes bent in curves of large radius were experimented on; some of these are illustrated in the diagram (figs. 3 to 7). The tubes are drawn accurately to scale. The radius in centimetres of the centre line of the curve is in each case given by the number printed at one end of each tube. The drawings of the stream-lines in fig. 2 are from sketches and photographs of some of the experiments.

In fig. 3 (2) the filament *a* strikes the outer wall at A (which is near the central plane of the tube bend), where it spreads out into a flat band and after following the wall of the tube it strikes the inner wall at A′ and then takes the form of path shown; a section of such a colour band after leaving A′ is usually curved.

In fig. 3 (4) the colour bands *b*BB′ and *c*CC′ illustrate the effect of increasing the velocity, *c*CC′ being at a mean velocity of flow of 3·7 cm. per sec., whilst *b*BB′ is at a velocity of 11 cm. per sec. In fig. 3 (6) the band *d*DD′ after leaving D′ breaks into branches, the main portion D′*d*′ flowing near the centre of the outlet limb whilst D′*d*″ flows near the inner wall of the tube.

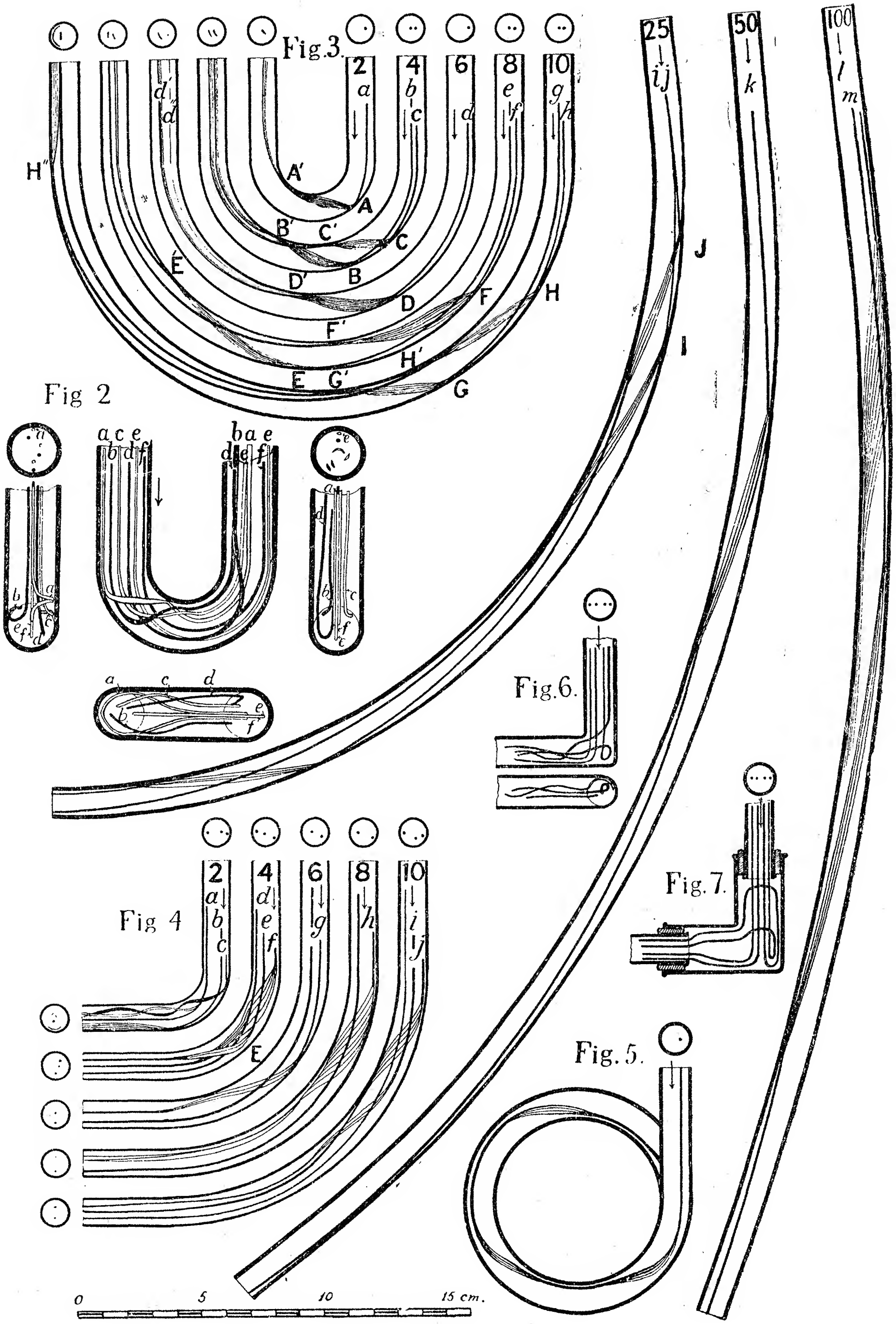
Fig. 3.
Fig 2
Fig. 6.
Fig. 7.
Fig 4
Fig. 5.
25
50
100
0
5
10
15 cm.

In fig. 3 (8) the line *f*FF′, taken at a velocity of 4·6 cm. per second, is of the same character as the lines previously described; after striking at F, it spreads out into a wide band, collects at F′ and leaves the tube in a fairly regular band of colour. The line *e*EE′ shows the effect of increasing the velocity to 18 cm. per second.

In fig. 3 (10) the line *g*GG′ is at a velocity of 17·5 cm. per second and the line *h*HH′ is at a velocity of 5·5 cm. per second, just sufficient for the colour band to strike the outer wall of the curve at H″, the band then spreads as shown in the sketch.

The effect of increasing the velocity in a curved tube is to increase the curvature of the filaments; for example the band H′H″ which is shown touching the tube at H″ would pass down the outer straight part of the tube without touching it if the velocity of flow is increased; other examples of this are given in the right-angled bend fig. 4 (2) and in fig. 1, *cc′c″*.

Results in Tubes of large Radius.—The same general results are obtained in tubes in which the radius of curvature of the tube length is large; fig. 3 (25) illustrates the effect of doubling the velocity of flow in a tube 1 cm. diameter bent to a curve of 25 cm. radius; the line *j*J (velocity 5·5 cm. per second) shows the repeated crossing of the colour band; *i*I is at double the velocity of flow (11 cm. per second). The increased curvature of the band at the higher velocity is again apparent.

The filament *k* in fig. 3 (50) and *l* in fig. 3 (100) show that, even when the curvature is very small, if the curve is sufficiently long the stream-lines will all strike the outer wall and follow the surface of the tube to the inner wall. The filament *m* in fig. 3 (100) enters the straight part of the tube in the central plane close to the outer wall; it spreads out into wide bands both above and below the central plane, and after crossing the tube opens out into two bands which remain uncombined for the whole remaining length of the tube, the inner radius of the bend being quite free from colour. In a longer tube these bands would cross over again to the outer radius, as is shown in the coiled tube, fig. 5, where all the stream-lines repeatedly cross from the inner wall to the outer wall and back.

In a straight tube the colour bands remain distinct and the surrounding water is not tinted; in curved tubes after the colour bands strike the walls of the tube, although the bands can be distinctly traced, some of the colouring matter is dispersed into the surrounding water, the outlet water being tinted.

In a coiled tube of several convolutions the distinctive character of the colour filament is gradually lost and after passing through several coils can scarcely be traced.

Results in right-angled Bends.—In the series of right-angled bends illustrated

in fig. 4, the lines *a*, *b*, *c*, in (2) were taken at a velocity of 10·5 cm. per second; when the velocity was increased to 15·2 cm. per second the positions of all the lines changed slightly, the line *a*, which at the lower velocity was in the position of the regular curve shown, broke up at the higher velocity into two branches, one of which formed a spiral vortex near the central plane of the tube and interlaced with the line *c*.

The position of the filament *b* was arranged so that it struck the extreme part of the outer curve, where it scattered as shown; at the increased velocity the line *b* passed through the outer straight tube without scattering.

In (4) the velocity is 7·3 cm. per sec., the line *f* strikes the bend below the central plane and crosses over close to the surface of the tube; other lines, such as *e*, which are above the central plane, follow paths shown at *e*E, whilst the lines represented by *d* nearer the central plane and the inner surface of the tube pass around the bend in an unbroken curve.

In (6) the velocity is 12·5 cm. per sec., the line *g* crosses under the other line, which passes through in an unbroken curve.

In (8) the velocity is 8 cm. per sec., the line *h* is close to the side of the tube near the central plane, it spreads immediately on entering the curved part, crosses the tube, and collects inside the bend, then leaves the bend in separate filaments; the other stream-line passes freely through the tube.

In (10) the velocity is 10 cm. per sec.; the results are very similar to that shown in (4).

The results obtained in sharp right-angled elbows are shown in figs. 6 and 7. The curious looping of the lines in fig. 7 will be understood from the somewhat similar loop shown in fig. 6.

The table on p. 125 is given to indicate the range of velocities employed, but the experiments were of a qualitative rather than of a quantitative character.

The U-tube, fig. 2, is 1·7 cm. internal diameter, all the others are 1 cm. diameter. The lengths of the curved part and the total lengths of each tube are given in Column 2. In each case the straight parts of the tube at both ends are of equal length.

Except in fig. 2 a connecting tube, 20 cm. long, was used in the position JJ, fig. 1; this tube tapered from 2 cm. to 1 cm. diameter for 10 cm. of its length, and was 1 cm. diameter for the remaining 10 cm. For fig. 2 the connector was only 4 cm. long, and tapered from 2 cm. to 1·75 cm. diameter.

The head in the tank varied from 20 to 30 cm.

Precautions taken in the Experiments: (*a*) To ensure the equal velocities of flow of the colour filaments and the surrounding water.—Before using

1. Fig.	2. Length of tube, cm.		3. Radius of curve, cm.	4. Temp. °C.	5. Mean velocity of flow in diagram, cm. per sec.	6. Turbulent motion, cm. per sec.	7. Critical velocity by Reynolds' formula.
	Curved part.	Total length.					
Fig. 2	7·8	34·8	2·5	17·0	3·5	7—8	12·8
Fig. 3 (2) ...	6·3	50·0	2·0	18·0	*a* 10·0	17—27	21·5
Fig. 3 (4) ...	12·6	50·0	4·0	18·0	{*b* 3·7, *c* 11·0}	17—21	21·5
Fig. 3 (6) ...	18·8	50·0	6·0	18·5	*d* 7·8	18—20	21·3
Fig. 3 (8) ...	24·1	50·0	8·0	18·0	{*e* 18·0, *f* 4·6}	18—23	21·5
Fig. 3 (10) ...	31·4	50·0	10·0	18·0	{*g* 17·5, *h* 5·5}	20—26	21·5
Fig. 3 (25) ...	50·0	60·0	25·0	19·0	{*i* 11·0, *j* 5·5}	19—21	21·0
Fig. 3 (50) ...	50·0	60·0	50·0	18·0	*k* 10·0	20—21	21·5
Fig. 3 (100)...	50·0	60·0	100·0	18·0	{*l* 12·6, *m* 6·4}	20—21	21·5
Straight tube	—	60·0	∞	16·0	—	19—21	22·5
Fig. 4 (2) ...	3·1	13·1	2·0	19·0	10·5—15·2	18—20	22·5
Fig. 4 (4) ...	6·3	16·3	4·0	19·0	7·3	19—21	22·5
Fig. 4 (6) ...	9·4	19·4	6·0	19·0	12·5	18—20	22·5
Fig. 4 (8) ...	12·6	22·6	8·0	19·0	8·0	19—21	22·5
Fig. 4 (10) ...	15·7	25·7	10·0	19·0	10·0	19—21	22·5

the arrangement of nozzles and colour supply sketched in fig. 1, the author designed an apparatus for a single filament of colour which acted automatically so as to give equal pressures on the colouring liquid and the flowing water; it could be so arranged that at any pressure the coloured liquid would ooze very gently into the flowing stream.

In other tests the colour was allowed to accumulate in the tube BC, fig. 1, when no water was flowing; the colour was then shut off and water allowed to flow through the tube, the paths of the stream-lines could be distinctly traced, following the same general directions as in the case of the regular filaments.

The motion of the solid particles referred to on p. 129 is an additional proof of the effect produced not being due to the filaments having a higher velocity than the surrounding water.

The arrangement described above for single filaments was used for high pressure experiments in metal pipes, which were 150 cm. long and 1 cm. diameter. Between these pipes and the colour distributing nozzles was interposed a converging tube which was connected to the metal pipe by a glass tube, 15 cm. long, of the same diameter as the metal pipe; a similar glass tube was connected to the outlet end of the metal pipe. When the metal pipe was kept straight the colour filament showed distinctly in the

glass tube at the outlet end; when the metal pipe was bent into a slightly curved form the colour filament no longer appeared in the glass tube at the outlet end as a thread of colour, but, if visible, it was as a flat band of colour, or it was more or less dispersed into the surrounding water.

Long, straight, glass tubes of from 1 to 2 metres long were substituted for the metal pipe, and when curved tubes were connected at the outlet end the same effect was produced as when the intervening connection was only a few centimetres long.

(*b*) Establishment of a steady *régime*.—From the preceding section (*a*) it will be seen that in some of the experiments the tubes were sufficiently long to ensure that the filaments and water had settled down to a steady *régime*.

In all the experiments the brass tube A, fig. 1, containing the nozzles for colour filaments was close to the tank, but between A and the tube experimented on there was interposed a converging tube, the dimensions of which are given on p. 124. This tube was of sufficient length to establish steady flow, as will be seen by comparing Columns 6 and 7 of the table.

Column (6) gives the commencement of the turbulent flow, Column (7) the critical velocity as calculated by Reynolds' formula. The same general results were obtained at low velocities when a steady *régime* is produced in a fairly short pipe at velocities far below the critical. In the **U**-tube, fig. 2, the connecting tube was short, and unsteady motion commenced at a much lower velocity than is given by Reynolds' formula. The turbulent motion given in Column (6) and the calculations in Column (7) are for the straight part of the pipe.

Comparison between the Flow of Water in Bends of Open Channels and of Closed Pipes.—Prof. James Thomson,* in his theory of the transfer of solid particles along the bed of a river from the outer to the inner bank, has shown that the centrifugal force of the more rapidly moving water near the surface overcomes that of the water close to the bottom, which is retarded by the friction of the bed of the river. Prof. O. Reynolds† has adopted this theory in his work "On Certain Laws relating to Rivers and Estuaries."

Thomson's experiments were carried out in open channels, and he has suggested that the theory of flow in curved channels is applicable to pipe bends. In introducing the theory he states that "a stream flowing along a straight channel, and thence into a curve, must flow with a diminished velocity along the outer bank and an increased velocity along the inner bank." The author's experiments show that the motion at the commence-

* 'Roy. Soc. Proc.,' May 4, 1876, vol. 25, and June 21, 1877, vol. 26.

† 'Report Brit. Assoc.,' 1887, and 'Sci. Papers,' vol. 2, p. 329.

ment of the curve of a pipe bend is not that of a "free" vortex, for the velocity is greater near the outside than it is near the inside of a curve.

There is another difference between the two cases. In an open channel there is freedom in a vertical direction, and, as Thomson has pointed out, the difference of pressure between the inner and the outer banks causes the surface of the water to be inclined from the inner to the outer bank of the curve. No such freedom is possible in a pipe which is running full, hence it is probable that the curvature of the stream-lines is greater and the effect of pressure on the transfer of water from the outer to the inner curve is more pronounced in a pipe than in a channel.

In experiments on **U**-shaped open channels of semicircular section, about 1 cm. radius, the author has noticed that the flow of water near the surface is retarded, for if a filament enters the bend just below the surface MN in the position of 2, fig. 9, it divides so that a part goes under the stream, as in fig. 9; another part of the filament follows a somewhat similar course near the surface of the water and flows towards the centre of the stream, where it is carried around near the central curve of the bend. Filaments entering close to 1 behave in the same way, except that some of the colour is in this case carried slowly around the bend quite close to the outer radius.

With these differences between open channels and pipes the following explanation may be looked upon as an experimental confirmation of Prof. J. Thomson's theory when applied to curved pipes.

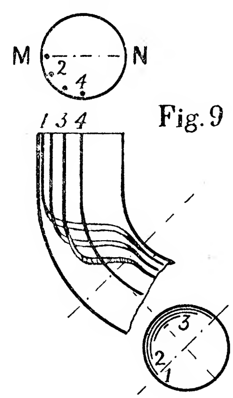

Fig. 9

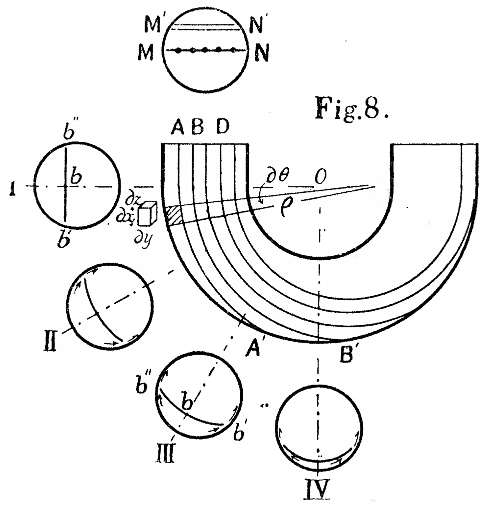

Fig. 8.

Motion in a Plane Sheet Perpendicular to Central Plane of Bend.—Consider a set of stream-lines flowing through the straight part of a pipe in a plane sheet which is at right angles to the central plane of the **U**-tube as shown

at B and at $b''bb'$ (fig. 8) where the circles at I, II, III, and IV represent sections of the tube taken along the radial lines OI, OII, OIII, and OIV respectively. Since the stream-lines near the centre b of the sheet are flowing at a higher velocity than those nearer b' and b'', it follows that when the sheet enters the bend, the force required to make the stream-lines in the centre of the sheet (at b in section I) tend to follow the curve of the bend will be greater than the force required nearer b' and b'', that is to say, the pressure between b and the outer wall of the bend will be greater than the pressure nearer b' and b'', and a flow of water will take place along the path of least resistance, *i.e.* from the region of greater to the region of less pressure, in the directions shown by the arrows in II, III, and IV. The centre portion of the sheet will gradually approach the outer wall, whilst some portion of the water near b' and b'' will be carried round the inner wall of the tube.

Motion in a Sheet in the Central Plane of the Bend.—Consider the stream-lines flowing in the central plane MN of the tube (fig. 8). Changes in pressure above and below the central plane will have no effect in disturbing the position of the lines, since the tube is symmetrical on both sides of the plane MN. In any other sheet M′N′ which was parallel to the central plane before it entered the curved part, since there are less stream-lines, and the velocities are less than in the plane MN, the pressure at M′ will be less than the pressure at M, and the pressure at N′ will be greater than the pressure at N; hence there will be a flow of water from M to M′, that is to say, the water close to the surface of the tube, which in a straight tube is at rest, will even in a slightly bent tube be set in motion. As the flow of water from between a stream-line and the tube wall takes place, the stream-line will gradually approach the outer wall of the bend, the displaced water flowing around the walls of the tube from the outer to the inner wall of the bend. After entering the bend the sheet M′N′ becomes inclined in the direction of a normal to the curves $b''bb'$ (fig. 8), as is shown by the deviation of the filaments from the central plane in the left-hand view of fig. 2.

Motion of the Filaments near the Walls of the Tube.—The order in which the stream-lines flow around the walls is shown in fig. 9. A filament which approaches the curve at the outer radius of the bend strikes the tube and divides into two parts, each of which crosses a half circumference of the tube to the inside, as shown at 1. A filament at 2 which approaches farther from the central plane MN flows inside the filament 1. A filament 3 flows inside 2, and so on; this is represented in the lower section of the tube in fig. 9.

It was often noticed that the colour filaments in the position of 2 and 3 crossed the tube in small waves or ripples, showing the approach of unstable motion, which ultimately leads to the mixing of the colour filaments with the surrounding water.

After reaching the inside of the tube the re-crossing always occurred in the half of the tube in which the filament entered, or in a tube of regular bore, the stream-lines are reflected back so as not to cross the central plane MN. This reflection is shown in some of the diagrams as in fig. 3 (10) and (25), and in the coiled tube fig. 5.

Turbulent Motion.—The experiments described above were carried out at velocities sufficiently low to give unbroken motion, but in all cases the effect of increasing the velocity was observed, and, although it was naturally impossible to trace the colour filaments for turbulent motion in the same way as has been done for steady motion, by increasing the quantity of dye or by placing finely divided solid matter in the tubes and carefully increasing the velocity until turbulent motion was reached, it was observed that the same general features hold good for turbulent motion. For example a layer of sand placed along the inside of the tube at aa' in fig. 1, in which the central plane of the tube is vertical, will not go around the outer radius of the **U**-tube but will follow the path $a'a''$. The author has shown that, when water is flowing at high velocity in a metal pipe bend, if a tube communicates from a' to a'' outside the tube a continuous stream of water is carried through the external tube from a' to a''.

Summary and Deductions.—The experiments show that when water is flowing at low velocities in a straight tube of uniform bore, filaments of colour maintain their form and relative positions, but when entering upon a curved portion of a tube some of the filaments spread out into bands of colour and cross to the inner part of the tube, travelling round its section close to the walls. If the curvature is sufficiently large or the curve sufficiently long, all the filaments would be affected. Other experiments in **U**-tubes seem to suggest that slipping may take place concomitant with the surface flow at the walls of the curved part of the tube. A quantity of dye having been spread over the whole of the surface of the tube, when water was allowed to flow through the tube, even at extremely low velocities, the colour disappeared immediately from the outer wall of the bend, more slowly from the inner wall, and very slowly indeed from the straight part of the tube.

In the experiments it was observed that as the velocity of flow increased there was an increase in curvature of the stream-lines. It is inferred that the resistance to flow along the tube walls from the outer to the inner wall does not vary as the velocity directly, as in the ordinary viscosity equation,

but it varies as the velocity raised to a power n, where n is greater than 1, and probably greater than 2.

Except for the stream-lines near the walls of the tube the flow in a curved tube at low velocities appears to be in accordance with the viscosity law. The increased resistance referred to above applies to the water which has impinged upon the walls and is in its circuit along the walls of the pipe.

If a pipe is not perfectly straight, the flow for the whole section of the pipe cannot be wholly viscous flow, since associated with viscous flow there is always some surface flow, that is to say, there is "skin friction," the effect of which is to increase the resistance of the pipe and to lessen the total discharge; or, for a bent pipe, n is greater than unity in the formula $S = Kv^n/m$.

In the author's previous experiments referred to on p. 119, it was shown that the increased resistance due to curvature of a pipe was relatively greater at velocities below the critical velocity than at velocities which give turbulent motion in a straight pipe. This relatively greater resistance at low velocities is probably due to the generation of "skin friction," which would not exist in a straight pipe of the same area at the same velocity, whereas the "skin friction" already existing is merely augmented at velocities which would cause turbulent motion in a straight pipe.

Although surface flow and viscous flow may exist together in a curved pipe, it was observed that in U-tubes and in angle pipes whilst the filaments in the straight pipe before reaching the walls of the bend continued unbroken up to the usual critical velocity in a straight pipe, the filaments flowing through the straight pipe after leaving the bend usually broke up at velocities much below the critical velocity. The surface flow which commenced in the bend generated vortices which persisted in the water flowing through the outlet straight part of the pipe. This shows that the effect of a pipe bend or of an angle is not only to increase the resistance to flow in the bend itself, but also to increase the resistance in the contiguous straight pipe after the water has left the bend.

This agrees with the results obtained by investigators who have experimented on the loss of pressure in the pipe bends used by engineers.

The foregoing experiments indicate that, where it is beneficial to break up the regular lines of flow in a pipe, a curved pipe is more effective than a straight one. They show, for example, that in a tubular boiler or in a condenser of a steam engine, curved pipes would be more efficient than straight pipes, for when water is flowing at low velocity in a straight pipe, the water near the centre of the pipe section does not approach the sides during its passage through the pipe, but in a curved pipe the water is continually

changing its position with respect to the sides of the pipe, and the water which is flowing near the centre at one part approaches the sides as it moves through the pipe, and flowing near the sides it exerts a "scouring" action on the pipe walls, thus increasing the effectiveness of the pipe surface in transferring heat.

Secondary γ-Rays produced by β-Rays.

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When the cathode rays of a vacuum tube impinge on any material they produce the X-rays, which are not deviated by a magnetic field, and are much more penetrating than the cathode rays which produce them. We might, therefore, expect that when the β-rays from radioactive substances impinge on a plate, similar penetrating rays would be emitted from the plate. Such a penetrating type of rays, the γ-rays, is almost invariably associated with the β-rays, but it has generally been thought that these γ-rays are due to the expulsion of the β-ray from the radioactive atom. In some cases they are certainly not due to the impact of β-rays on external objects, the γ-rays of radium C being an instance of this. Here the γ-rays come from the radioactive atoms, and in such amount that they effectually mask the possible production of γ-rays by β-rays as the experiments of H. Starke* show.

Starke attempted to find whether β-rays did produce γ-rays.† He used for this purpose 6 milligrammes of radium bromide contained in a very thin glass tube, which let most of the β-rays out. The γ-rays from this ionised the air in an electroscope, the walls of which were thick enough to absorb all the β-rays. He looked for an increase in the ionisation when various materials were placed just behind the radium. He found practically no difference in the reading, and, from that and a similar experiment in which he deflected the β-rays away from the electroscope by a magnetic field, concluded that no measurable γ-radiation was caused by the β-rays of radium C.

* H. Starke, 'Le Radium,' February, 1908, p. 35.

† In this paper a distinction is drawn between primary γ-rays and secondary γ-rays. By primary γ-rays are meant γ-rays coming from the radioactive atom. By secondary γ-rays, γ-rays produced by the impact of β-rays on external materials.